USE OF SURFACE SKIMMING SH WAVES TO MEASURE THERMAL AND RESIDUAL STRESSES IN INSTALLED RAILROAD TRACKS

George A. Alers and Alfonso Manzanares

Magnasonics, Inc.
215 Sierra Drive, SE
Albuquerque, NM 87108

INTRODUCTION

The stress level in a material is usually measured with an electrical resistance strain gage attached permanently to the object. Such an approach actually yields only the change in stress when a load is applied and thus gives no information on the state of residual or thermal stresses that may be present in the unloaded material. X-ray methods can be made to yield absolute stress levels but they are time consuming and only give values characteristic of the first few microns of the surface layer. Elsewhere in this volume, several articles {1} can be found that describe magnetic methods that infer stress in steel from the magnetic field dependence of certain magnetic properties. Not only are these methods applicable only to steel but they suffer from the fact that they must be calibrated for the specific alloy being used and are based on experimentally established correlations between the stress and the particular quantity being measured. Ultrasonic techniques, on the other hand, are generally applicable to any material and are much less susceptible to uncertainties arising from the empirical tests used to calibrate them. However, like the electrical resistance strain gage, they are normally used to measure only relative changes in stress because the rolling textures that are often present in commercial structural materials introduce effects that cannot be distinguished from residual or thermal stresses.

This paper describes an ultrasonic method that is not influenced by texture and hence is capable of yielding the absolute stress level present in the material through which the sound wave has traveled. Since the sound skims along the surface and the wavelength is of the order of a millimeter, the method actually measures the total stress present in a millimeter thick layer at the surface. In principle, making measurements on all surfaces of the part would allow the residual stresses to be accounted for and removed from consideration because their sum around the free surface must add up to zero.

An important application of this approach is to the measurement of the thermal stress induced in welded railroad rails by the heat of the sun or the cold of a winter night. Modern railroad practice is to weld rails together in order to eliminate those sources of rail fracture caused by cracks at bolt holes and gaps between rails at the joints.

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Unfortunately, this leads to large compressive stresses when the constrained ribbon of steel gets hot in the summer and large tensile stresses when it gets cold in winter. As a matter of fact, these stresses are actually large enough to cause buckling or tensile failure under obtainable weather conditions. Thus, there is a need for a nondestructive test probe that can be applied to the web of an installed rail and measure the local stress condition to see if it is approaching a critical level so that remedial actions can be taken.

THE SURFACE SKIMMING SH WAVE TECHNIQUE

Stress measurements based on ultrasonic techniques depend on the fact that the velocity of sound is a linear function of the stress. It is called the acoustoelastic effect {2} and is most accurately implemented in the field by measuring the birefringence introduced by the stress. That is, by measuring the difference in transit time between two shear waves propagating through the thickness dimension of a part but polarized parallel and perpendicular to the direction of the stress. In an isotropic medium, this difference is a well defined linear function of the stress and the constant of proportionality can be determined by calibration experiments performed in a laboratory on alloys of similar composition and heat treatment. Unfortunately, most structural materials are anisotropic because their basic physical properties depend on the direction in which the measurement is taken relative to the forming or rolling direction used to define the shape of the part. Railroad rails fall easily into this anisotropic class of metals because they are rolled and straightened with the length dimension highly preferred.

Recently there have been advances in the theory of wave propagation in media that are both anisotropic and supporting a stress {3,4}. These studies show that the texture effects can be separated from the stress effects so that by making certain specific ultrasonic wave velocity measurements {5}, the texture effects can be measured and subtracted from the stress effects. The most direct and simple method of eliminating texture effects from the stress measurement is to use a general property of anisotropic media that states that an interchange of the propagation and polarization directions for a shear wave propagating along a symmetry axis in a stress free medium will not change the velocity of sound. In the presence of a stress, it has been demonstrated {6} that the difference in velocity when the polarization and propagation directions are interchanged can be related directly to the stress by the simple equation

$$V_{ij} - V_{ji} = \sigma_{ii} V_{ij}/2G \tag{1}$$

where V_{ij} is the velocity of a shear wave propagating in the i direction and polarized in the j direction, σ_{ii} is the stress in the i direction and G is the shear modulus of the material.

By using Electromagnetic Acoustic Transducers (EMATs) {7}, it is possible to excite or detect a shear wave that skims along the surface and is polarized in the plane of the surface {8}. Such waves are called surface skimming shear horizontal (SH) waves. By mounting a transmitter/receiver pair of these transducers to send such a wave along the i symmetry axis, the velocity V_{ij} can be measured. Since SH waves are polarized in the plane of the surface, such a wave is automatically polarized in the j direction. By simply rotating the pair of transducers about the axis perpendicular to the surface, the propagation direction can be brought around to the j axis and the polarization will then be parallel to the i axis. The velocity then measured is V_{ji}. If there is a difference in the transit times at the two orientations of the transducer pair, then a stress must be present and its magnitude can be used to calculate the absolute stress level through Eq. (1).

The exact theory {6} for sound wave propagation in stressed and anisotropic media shows that the transit time depends on the angle θ between the line joining the transducers and the i axis through an equation of the form

$$\tau(\theta) = \tau_o + S \cos 2\theta + T \cos 4\theta \tag{2}$$

where T is a constant that depends only on the preferred orientations of the grains in the material, i.e., the texture. The most accurate procedure for making a stress measurement that also verifies the theory is to measure τ as a function of θ and to fit the data with a curve of the form of Eq. (2). The coefficient of the $\cos 2\theta$ term that best fits the data can be used to deduce the stress since

$$\sigma = -4GS/\tau(0) \tag{3}$$

EXPERIMENTAL APPARATUS

During the past several years, electronic apparatus and EMATs specifically designed to utilize the SH wave method have been assembled and tested at Magnasonics {9}. The most successful type of EMAT for exciting and detecting the requisite SH waves consists of a meander coil with the magnetic field parallel to the long wires of the meander {10}. This particular design requires a pulsed electromagnet to generate the high tangential magnetic fields required by the magnetostrictive coupling mechanism involved. Early experiments shows that because these fields were high, the iron acts as if it were saturated and variations in the velocity of sound that accompany domain wall motion are eliminated. The EMATs used had to be operated at 2 MHz (wavelength = 0.06 inches) so that the separation distance between the transmitter and receiver could be made small enough to fit on the web of a rail while still being large enough to allow the receiver electronics to completely recover from the large currents in the transmitter during generation of the acoustic waves. A second reason for operating at 2 MHz was to be assured that the radiation pattern of the sound waves into the bulk of the rail would be a narrow beam near the surface with no side lobes that could put energy into the receiver by reflection from the opposite side of the web. The final EMAT configuration placed the EMAT coils 1.25 inches apart so that the transit time for a surface skimming SH wave between the transmitter and receiver was 10 microseconds. In order to detect a 2 ksi stress, Eq. (1) requires that a time difference of 1 nanosecond be detected. This was accomplished through the use of a Hewlett-Packard Model 5335 Universal Counter which was triggered to start counting when the transmitter was activated and to stop counting when a particular zero crossing in the received tone burst arrived.

EXPERIMENTAL VERIFICATION

Verification of Eqs. (1) through (3) has been demonstrated on structural steel beams loaded by a compression test machine as described in previous volumes of these proceedings {9}. Included therein, is a demonstration that the technique can measure a thermal stress as would be developed in welded rail. To accomplish this, a box beam was heated while its length was held constant in a compression test machine. The angular dependence of the transit time was used to measure the stress.

For a 62°C temperature change, the coefficient S in Eq. (2) predicted a stress level of 28 ksi while a calculation based on the thermal expansion coefficient predicted 29 ksi. During the course of subsequent experiments with the box sample, the anvils of the compression machine became accidentally misaligned and the parallel faces on the end of the box became permanently deformed out of parallelism. As a result of continued loading of the box at various times, the box took on a slightly curved or bowed shape when it was in the free or unloaded state. Such a condition represents a classic example of an elastic body in which a compressive residual stress is present on the convex face while a balancing tensile residual stress is present on the concave face. Figure 1 shows the angular dependence of the SH wave transit time on the box sample in its bowed condition with no external forces applied. On the concave face, the coefficient S is a negative 4.6 nanoseconds which corresponds to a tensile stress of 20 ksi while on the convex face, the coefficient S is a +4.3 nanoseconds which corresponds to a compressive stress of 10 ksi. Thus, it can be concluded that the SH wave method does measure the absolute level of stress in a part and therefore can be used to measure residual stresses on parts with no loads on them.

APPLICATION TO RAILS

Figure 2 shows a schematic drawing of the EMAT and magnet configuration finally developed for making stress measurements on the web of a rail that has already been installed in the field. Not shown in this drawing is a support structure that holds the assembly in place while the magnet and its two EMAT coils are rotated about an axis perpendicular to the web face. A special pin on the rotating mechanism holds the magnet in a fixed angular orientation while a transit time is measured. After the transit time has been displayed by the counter, the pin is moved to a new hole which rotates the magnet by exactly 10 degrees and a new measurement is taken. When 18 such measurements have been completed, the acoustic path of the sound waves will have been rotated through 180 degrees and curves like those shown in Fig. 1 can be plotted. A computer program then fits these data with the sum of $\cos 2\theta$ and $\cos 4\theta$ angular dependence terms and displays the values of the coefficients S and T that give the best fit to the data. Equation (3) was then used to convert the measured S value into a stress.

Inspection of Fig. 2 shows that the web of a railroad rail is not flat but has a small curvature so the SH waves actually propagate on the surface of a cylinder. Since the EMAT coil support system has been carefully designed to hold the coils at a fixed separation even on slightly curved surfaces, the acoustic path between the coils can be expected to change as the pair of EMAT coils is rotated on the surface of a cylinder. In particular, the sound must follow a curved path with a radius of curvature equal to the curvature of the rail web when the two EMAT coils are aligned vertically while the sound will travel on a straight path

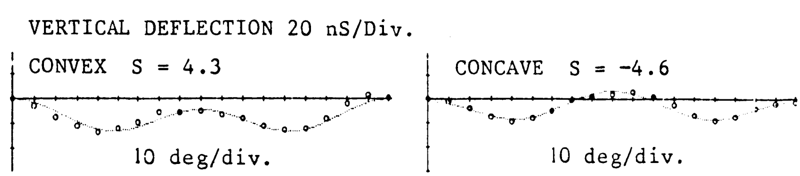

Fig. 1. Angular variation of the transit time for SH waves on the box beam after it had been permanently bowed by off-axis compressive loading.

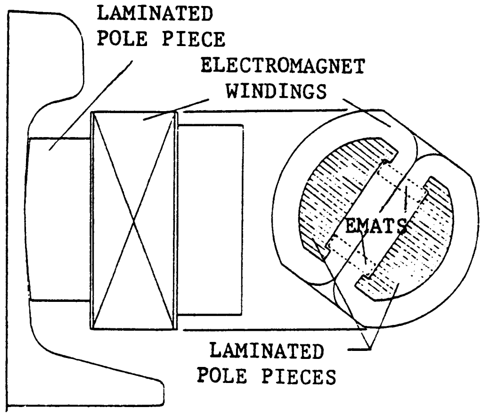

Fig. 2. Schematic drawing of the SH wave EMAT probe used to measure stress in the web of a rail.

when the coils lie in a horizontal line. To develop a correction for this curvature effect, we postulate that the path actually followed by the sound is below the surface by a small distance δ which is comparable to the wavelength. If the separation distance between the EMATs along the surface is a fixed distance L, then the path length L' followed by the sound under a surface with a curvature R can be calculated from the angle ϕ subtended by the distance L since

$$\phi = L/R = L'/(R\pm\delta) \quad \text{or} \quad L' = (R\pm\delta)L/R \tag{4}$$

where the + or − sign is used for concave and convex surfaces respectively. Using analytic geometry, it can be shown that the radius of curvature of a line on a cylindrical surface is related to the angle θ that the line makes with the directrix of the cylinder by the equation

$$R = r/\sin^2\theta \tag{5}$$

where r is the radius of the cylinder. Therefore, the transit time of a sound wave on a concave surface is

$$\tau = L'/V = L(1 + \delta\sin^2\theta/r)/V = \tau(0)(1 + \delta/2r) - \delta\tau(0)\cos 2\theta/2r \tag{6}$$

Combining this equation with Eq. (3), it follows that the coefficient S deduced from measurements of the angular dependence of the transit time measured on a concave surface with a curvature r will be related to the stress by the equation

$$S = -\sigma\tau(0)/4G - \delta\tau(0)/2r \tag{7}$$

which can be interpreted as saying that the curvature introduces an apparent tensile stress of strength $2G\delta/r$ which should be subtracted from the stress deduced from Eq. (3) to find the actual thermal or residual stress in the web of a rail.

In order to obtain a quantitative value for the curvature correction factor, four steel plates were prepared with one surface machined into a cylindrical shape. Two plates were concave with 20 and 16 inch radii of curvature while the other two were convex with the same curvatures.

Measurements of the angular dependence of the transit time were made on the curved surfaces and the S coefficients for each curvature was deduced from Eq. (2). By measuring the slope of the straight line to a graph of S versus $1/r$, δ was found to be 0.018" which is about one quarter of the wavelength and is consistent with the model postulated to account for the curvature effect. Therefore, the apparent stress introduced by the concave curvature of 16 inches on the web of a 132 pound per yard rail is 24 ksi in tension. The apparent stress introduced by the 10" convex radius of curvature on the head of a new rail is a compressive stress of 38 ksi.

The EMAT probe and electronic instrumentation described above were applied to a collection of short rail sections already available at Magnasonics. In order to demonstrate that the SH wave method actually measures the applied stress without any adjustable parameters, some of the rails were cut to a 12" length and flat parallel surfaces were ground on the ends so that the compression machine could apply a 200,000 pound compressive load parallel to the length of the rail. The procedure used was to measure the angular dependence of the transit time before and after application of a 13 ksi stress and to convert the observed change in the coefficient S into a stress change by using Eq. (3) and a $\tau(0)$ of 10 microseconds and a G value of 11,000 ksi. Table I shows the results obtained on five rails for several different locations of the probe on each rail's surface. Although the experiments were repeatable and most of them led to stress change values that were within the experimental error ($\pm$ 2 ksi) of the predicted value, a few were very far off. The origin of these few discrepancies has yet to be determined. Since the purpose of the experiments was to compare the theoretical predictions with experiments without any adjustable parameters, we conclude that the SH wave technique is a valid method of measuring the absolute stress in a material even though there are some cases where an as yet undefined effect causes a spurious result to be obtained.

During the course of these experiments, it was observed that the coefficient S was not equal to zero when there was no load applied and the measurement surface was flat. Such a result is to be expected if residual stresses are present in the rail samples. A survey of the literature showed clearly that residual stresses are common in finished rails because a wide variety of bending and pulling techniques are applied

Table I. Values of the stress change deduced from Eq. (3) when a 13 ksi compression stress was applied to various rail samples. (+ sign = tension; - sign = compression)

		Calculated Stress Change (Should read -13 ksi)		
Rail No.	Face	Exp. #1	Exp. #2	Exp. #3
SG	Web (left)	-12	-12	-13
	Web (right)	-10	-10	
	Base Center	-9	-7	
	Head	-12		
322	Web (left)	-10		
	Web (right)	+15		
	Head	-6		
321	Web (left)	-16		
	Web (right)	-15		
	Head	-3		
312	Web (left)	-8		
	Web (right)	+3		
324	Web (left)	-16		
	Web (right)	+1		

late in the manufacturing process to produce a straight rail. Much of the literature data and common sense indicate that there should be rapid variations in the residual stress across the base with extreme values near the center line where the web attached to the base. To verify the hypothesis that the SH wave method measures residual stresses, the angular dependence of the transit time was measured on the base of four unloaded samples at different locations relative to the centerline. The resulting S coefficients were converted to stress values using Eq. (3) and the results are shown in Table II. In all cases, the apparent stresses vary smoothly across the base except for Rail 312 which exhibited the unusual response to an applied load shown in Table I.

Since the sum of the residual stresses in the surface of a part in equalibrium must be equal to zero, it was deemed worthwhile to measure the value of the coefficient S at as many locations as possible around the surface of the four rail samples that are new and hence should not be complicated by the presence of service induced residual stresses in the top of the head. Table III shows the results of these measurements with the S values converted into apparent stress levels by Eq. (3). Those measurements made on the head and web have been corrected for the effects of curvature by removing a 24 ksi tension from the web data and a 39 ksi compression from the head data. With the exception of Rail 312, there seems to be a pattern in which the head is in compression and the base in tension as if the original rail had been straightened by bending it about an axis perpendicular to the web. In most cases the web appears to be in tension with an occasional difference between the left and right sides as would be the case for straightening the rail about an axis perpendicular to the head. A more detailed discussion of the apparent residual stress patterns shown in Table III must await a detailed stress analysis that takes into account the complicated shape of the rail cross section.

CONCLUSIONS

1. An EMAT probe has been developed that can be used on the head, web and base of a rail to measure the state of stress in a $\sim$1 mm thick layer of the surface.

2. Correction factors and calibrations that depend on the details of the composition and microstructure are not needed. A geometrical correction for curved surfaces on the head and web is needed and is now available.

3. It appears possible to measure the residual stresses left in a rail by the manufacturing process and by service.

4. Thermally induced stresses can be deduced if the residual stresses are taken into account.

Table II. Values of the presumed residual stress at several locations across the base of four rails. (Units are ksi).

Rail No.	Location relative to centerline (inches) 1.5	0.75	0
SG	-8	+5	+22
322	+52	+37	+43
321	+28	+43	+66
312	+45	-62	-44

Table III. Values of the apparent surface stress at various locations around four samples of new rail. The units are in ksi and a correction for curvature has been applied.

Location	SG	322	312	321	336 (used)
			Rail No.		
Head	-36	-52	+42	-57	-61
Web (left)	+25	+19	-21	+19	+51
Web (right)	+24	+41	+21	+29	+28
Top of base (left)	-9	-119	-66		
Top of base (right)	-30		-54		
Bottom of base					
Center	+22	+43	-44	+66	+8
3/4" off center	+5	+37	-62	+44	
1-1/2" off center	-8	+52	+45	+28	

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